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Hose Elements for Buoy Moorings: Design, Fabrication and Mechanical Properties

by

Walter Paul

July 2004

Technical Report

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Approved for Distribution:

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HOSE ELEMENTS FOR BUOY MOORINGS: DESIGN, FABRICATION, AND MECHANICAL PROPERTIES

ABSTRACT

This report describes the design of tire cord reinforced rubber hoses, which have found an application as mooring hoses for oceanographic and offshore aquaculture buoy systems. These hoses stand out due to their ruggedness and ability to significantly stretch under load. The ruggedness is achieved through a steam curing = vulcanization process of the completed hose, generating a similar toughness of the hoses like automobile tires. Elastic stretch ranges can be designed from 30 to 130 percent through variation of the arrangement of the load carrying tire cord layers in the hose body. The hoses can also be furnished with electrical conductors and possibly optical light-guides as part of the hose wall. This technical report describes the design, fabrication, and mechanical properties of the mooring hoses to allow engineers to custom develop hoses with tailored mechanical properties.

Figure 1 Gumby hose awaiting deployment in the Labrador Sea

1.0   DESIGN OF HOSE ELEMENTS
1.1   Hose Components

The hose is formed by hand wrapping over a steel mandrel thin layers of rubber sheets serving as inner liner, separation layers, or outer jacket. Reinforcement layers from tire cords embedded in rubber sheaths are sandwiched between the rubber layers. The reinforcement layers use woven nylon tire cord or Kevlar tire cord fabric that is arranged inside a thin rubber layer, see Figure 2. The woven cord fabric consist of a tightly spaced layer of parallel nylon or Kevlar tire cords (yarns) separated by thin cotton weft yarns. The cotton yarns provide even spacing of the nylon or Kevlar tire cords of about 25% of the tire cord diameter between the cords. Soft not vulcanized rubber is squished into, around, and over this open fabric to form thin sheaths. The sheaths are sliced to ribbons of required width to result in specified wrap angle with the tire cords running
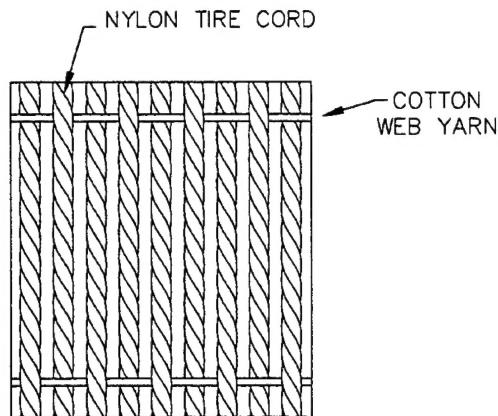
Figure 2: Woven cord reinforcement

parallel to the ribbon axis. Nylon tire cord layers are used as strength members, Kevlar tire cord layers are used as fishbite prevention layers.

1.2   Design Calculations

The design calculations require the following input: The hose inner and outer diameter, for the rubber layers the thickness of the individual layers and the elastic modulus. For the nylon tire cord fabric the load elongation curve of the individual cord, the number of cords per inch, and the ribbon width and thickness of the woven cord fabric for the specified wrap angle is needed. For the Kevlar tire cord fabric only the ribbon width is required, which assures a steep wrap angle at which the Kevlar cord layers will not be loaded when the hose is tensioned.

The cross sectional area of the rubber hose wall and the helical arrangement of the tire cord ribbons in the hose wall influence the load elongation properties of the stretch hoses. Basic modeling methods developed for textile structures like yarns and fabrics are modified to calculate the theoretical load elongation reactions of the nylon tire cord layers in the hose wall. The hose wall rubber load share is added as function of its linear elastic modulus.

The basic methods to calculate the load response of textile structures under strain have been developed mainly at the University of Manchester in England and MIT since about 1955. (Treloar et al, 1963; Hearle et al, 1969, Backer, S., 1971). They are adapted and expanded here to establish the theoretical load-elongation and fill pressure mechanics of the stretch hose nylon reinforcement as follows:

1.) Model the geometry of the helical nylon cord layers in the unstretched hose and the geometry change when the helical cord path is stretched.
2.) Compute, with assumed hose deformation conditions, the stretch of the elongated nylon cord layers
3.) Introduce the load elongation behavior of the nylon cords to obtain internal cord loads under known cord elongation
4.) Calculate the rubber hose wall load share at the selected hose elongation
5.) Sum up the internal nylon cord loads to obtain their resulting external load reaction and the buildup of fill fluid pressure in the hose cavity
6.) Add rubber hose load and nylon cord load to determine the hose total load and fill fluid pressure response to a given hose elongation

7.) Determine the end-cap load of the fill fluid pressure against the hose bulkheads. The end-cap load must be subtracted from the total hose load to obtain the hose net tension

8.) Repeat this procedure to obtain enough hose load elongation data points to establish the calculated load elongation curve and the calculated elongation versus fill pressure curve of the reinforced rubber hose

With these eight steps the theoretical load response to applied hose stretch is obtained. The load response to applied stretch depends on the hose reinforcement structure, steps 1 to 3, and 5 to 8, and on the rubber material response, step 4, 6, and 8. By repeating these steps for a large enough number of hose strain values, enough load reactions are computed to be able to draw theoretical hose load elongation curves, see step 8. The curves have to be verified by tests. The theoretical and experimental procedures are shown in Figure 3.
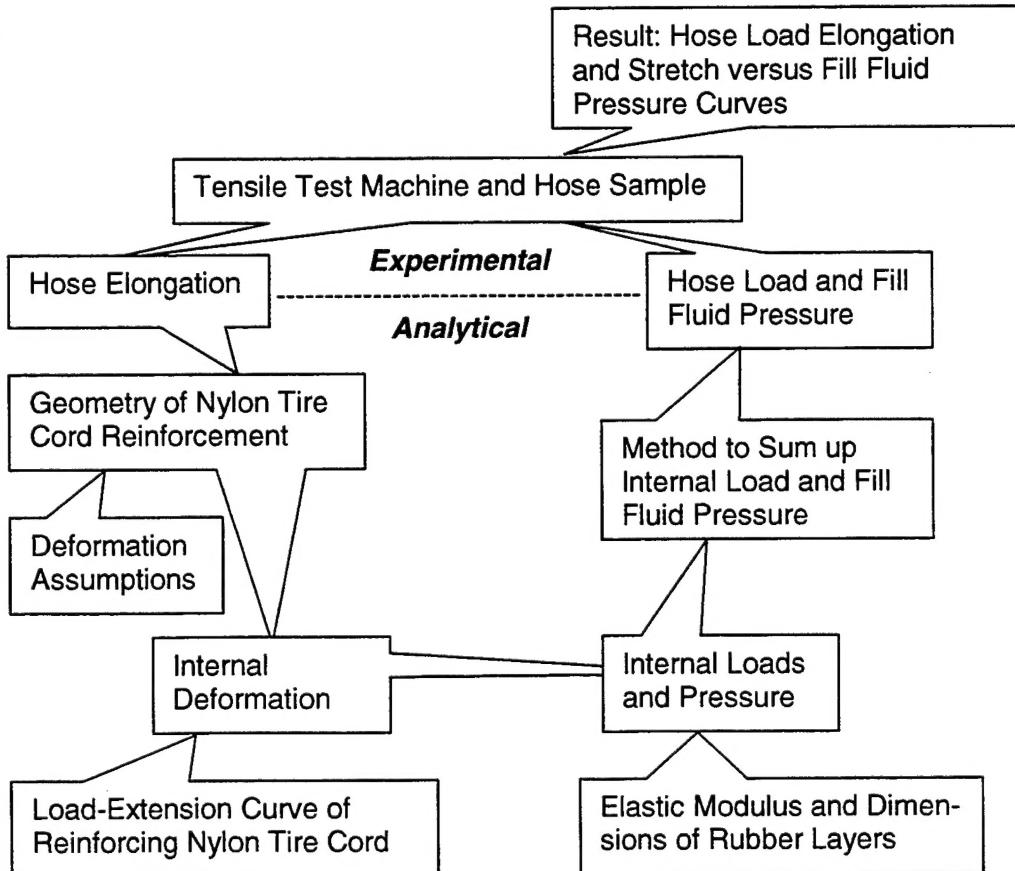
Figure 3: Experimental and Analytical Procedure to Obtain Load Elongation and Load Fill Fluid Pressure Behavior of Stretch Hoses

1.2.1 Geometry of Nylon Tire Cords in Stretch Hose

The cord geometry as helical path in the stretch hose is determined by the cord helix angle α and its wrap diameter d_w. Calculated data are the pitch length of the helical path p and the length of the spiraled cord l_c, see Figure 4:
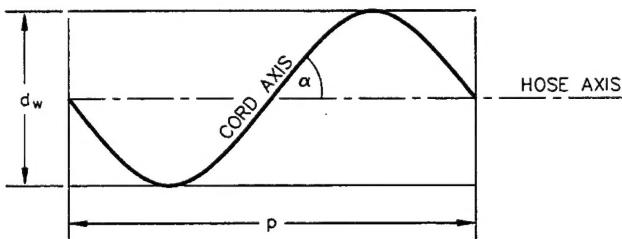
Figure 4: Helical path of tire cord in stretch hose

The helix length is determined by:

$$\tan \alpha = \pi \, d_w / p \qquad (1)$$

$$\text{and } \cos \alpha = p / l_c \qquad (2)$$

The geometry of the relaxed and stretched cord is compared in Figure 5.
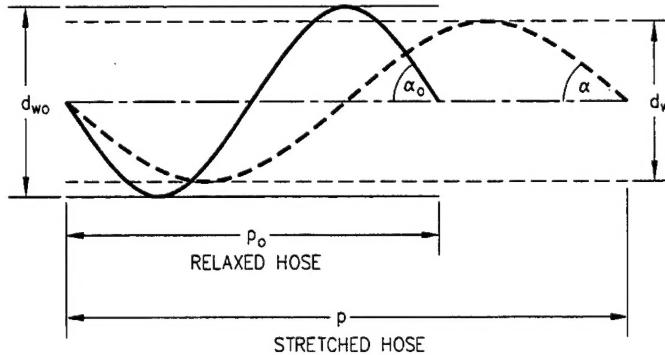
Figure 5: Side view of relaxed and elongated stretch hose

We introduce the following ratios to ease calculations:

Stretched hose length/Relaxed hose length $= \lambda_h = p_h / p_{h0} = (1 + \varepsilon_h)$ (3)

Stretched cord length/Relaxed cord length $= \lambda_c = l_c / l_{c0} = (1 + \varepsilon_c)$ (4)

where ε_h is the hose strain, and ε_c is the tire cord strain.

As <u>deformation assumption</u> for the stretching hose we select that the hose volume does not change due to the incompressibility of water as its fill fluid. For the unstretched dimensions we use the subscript $_0$, for the stretched dimensions there is no subscript. The hoses are filled with water. The volume of the hose, relaxed or stretched, stays constant and we can write:

$$p_{h0} \, d_{w0}^{2} = p_h \, d_w^{2} \qquad \text{[inch}^3\text{]} \text{ or with equation (3)}$$

$$d_w = d_{w0} \, \lambda_h^{-1/2} \qquad \text{[inch]} \quad (5)$$

The helical cord, rolled out in a plane, is shown in Figure 6
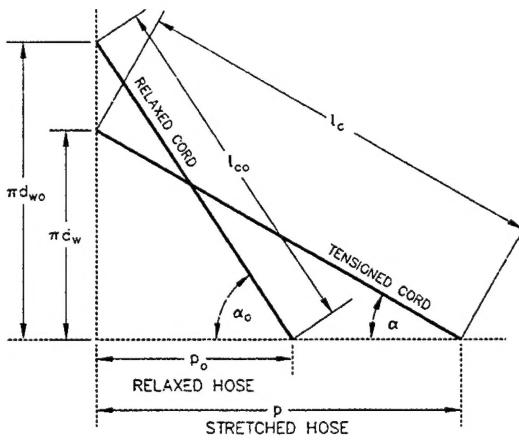
Figure 6: Helical cord path, rolled out on a plane in relaxed and tensioned stretch hose

The following geometrical relations can be determined from figure 6 and equation 5:

It is

$$\cos \alpha \ / \cos \alpha_0 = p_h * l_{c0} / l_c * p_{h0} = \lambda_h / \lambda_c$$

or $\quad \cos \alpha = \cos \alpha_0 * \lambda_h / \lambda_c \qquad (6)$

and

$$\tan \alpha / \tan \alpha_0 = (d_w * p_0) / (d_{w0} * p)$$

or $\qquad \tan \alpha = \tan \alpha_0 * \lambda_h^{-3/2} \qquad (7)$

with $1 + \tan^2\alpha = 1/\cos^2 \alpha_0$

Equation (6) becomes:

$$\lambda_c^2 = \lambda_h^2 * \cos^2\alpha_0 / \cos^2\alpha$$

$$\lambda_c^2 = \lambda_h^2 * \cos^2\alpha_0 \cdot (1 + \tan^2\alpha) \text{ with equation (7)}$$

$$\lambda_c^2 = \lambda_h^2 * \cos^2\alpha_0 + \lambda_h^2 * \cos^2\alpha_0 * \tan^2\alpha_0 * \lambda_h^{-3} \text{ or}$$

$$\lambda_c^2 = \lambda_h^2 * \cos^2\alpha_0 + \sin^2\alpha_0 / \lambda_h \qquad (8)$$

With equation (8) we calculate the nylon tire cord elongation ratio $\lambda_c = (1 + \varepsilon_c)$ at a given hose stretch ratio $\lambda_h = (1 + \varepsilon_h)$ and a selected wrap angle α_0. From the known cord load elongation curve we determine the tension F_c of a single nylon tire cord at each assumed cord elongation ratio λ_c under the constant volume (isochoric) deformation assumption of the tire cords in the hose body.

Results of equation (8) are shown in Figure 7. Figure 7 shows that with increasing cord layer wrap angles α_0 the stretch of the spiraled cord layer becomes smaller and smaller. At a wrap angle of about 54 degrees the cord elongation becomes zero and at larger wrap angles negative over significant initial constant volume stretch of the hose assembly. A shorter length of its helical path in the stretched hose forces the negative

cord elongation or buckling, impossible for non-textile hose wall components. The stretched hose is forced to a diameter reduction by the constant volume law. At wrap angles above 54 degrees the rubber hose wall components must first solely support the hose tension in response to hose stretch until a hose stretch is reached where the buckled tire cords start to pick up load and share the hose tension with the stretched rubber components, see Figure 7. The hose load elongation curve is very strongly dependent on the wrap angles of its counter-helical nylon strength member layers, allowing high stretching hose designs.
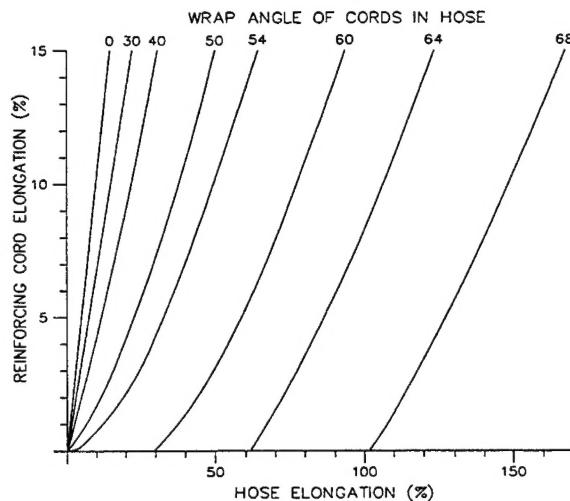
Figure 7: Elongation of stretch hose versus elongation of reinforcing cords spiraled inside hose wall under constant volume (isochoric) stretch

1.2.2 Determination of the number of Tire Cords in Hose Cross Section

The number of tire cords N is determined with help of Figure 8 from the width of the two nylon counter-helical tire cord reinforcing ribbons.
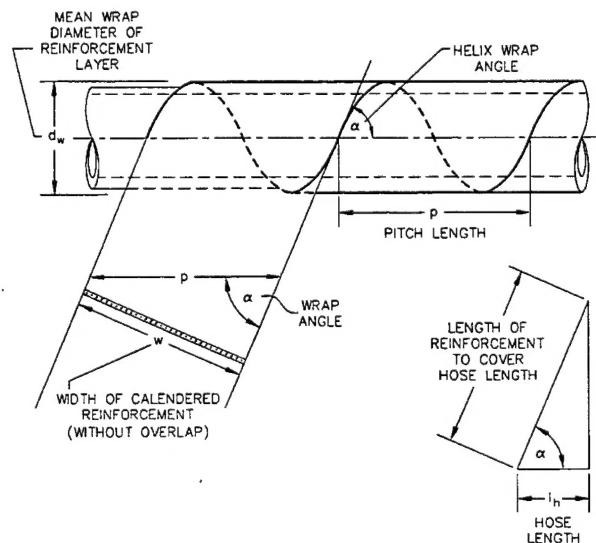

Figure 8: Dimensions of cord ribbons for wrapped counter-helical tire cord reinforcement

The cut ribbon width w_c can be calculated as:

$$w_c = p_c \sin \alpha_0 = \pi \, d_w \cos \alpha_0 \qquad \text{[inch]} \quad (10)$$

where p_c is the pitch length of one wrap, d_w the mean wrap diameter of the nylon tire cord layer in the hose wall, and w_c is the cut ribbon width of the reinforcement layer for a butted wrap. The total number of tire cords N in the hose wall with two counter-helical layers of reinforcement is

$$N = 2 * w_c * n_c \qquad \text{[inch]} \quad (11)$$

where n_c is the number of cords per inch of the nylon tire cord fabric used. We are using a woven cord fabric with 34 cords per inch of nylon 840 denier/2[1], each cord has a 0.022 inch diameter, and has a breaking strength of about 30 lbs or about 1,000 lbs/inch.

1.2.3 Determination of the "Chinese Finger" Effect of the Tensioned Nylon Tire Cords

The tensioned counter-helical nylon tire cords in the hose wall develop a choking pressure on the incompressible water filling inside the hose cavity. A cord bent around a cylinder with a 90 degree wrap angle generates pressure with the sheave formula, see Figure 9.

A tire cord under the tension P_c subjected to a partial wrap over a round surface generates a pressure force P_i :

$$P_i = 2 * P_c * \sin \beta/2 \qquad \text{[lbs]} \quad (12),$$

here β is the contact angle of the cord with the round surface.
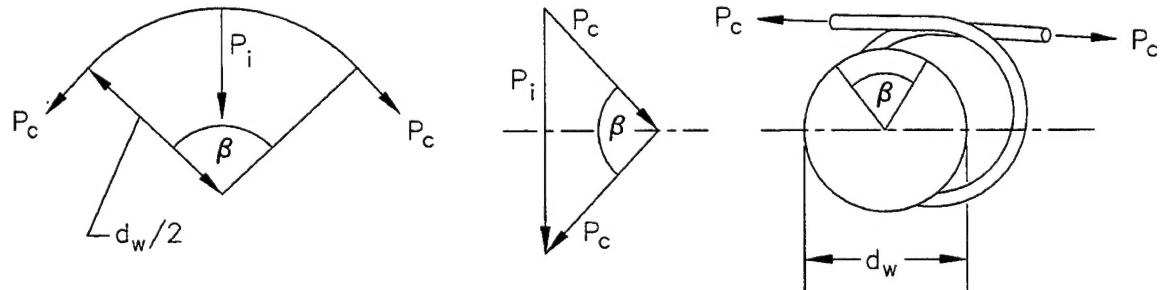
Figure 9: Cord Wrapped around Hose with $\alpha_0 = 90^0$

For a full 360^0 wrap the load P_i becomes:

$$P_i = 2 * \pi * P_c \qquad \text{[lbs]} \quad (13)$$

The pressure p_i developed under one wrapped cord is:

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[1] Denier is a textile unit with the dimension weight per unit length. 1 denier is the weight of a 9000 meter long fiber in gram. 840 denier is a fiber bundle which weighs 840 gram /9000 meter = 0.0933 gram/meter; or 840-2 denier, the tire cord we are using, weighs 0.1867 gram/meter.

$$p_i = P_i / A_c = 2 * \pi * P_c / (d_c * d_w * \pi) = 2 P_c / (d_c * d_w) \qquad \text{[psi]} \qquad (14)$$

where A_c is the area under one cord wrap. This is the so-called sheave formula.

For helically wrapped cords the wrapping radius is the radius of curvature ρ and the area under one helical wrap A_c is:

$$A_c = 2 * \pi * \rho * d_c, \text{ where } \rho = d_w / (2 * \sin^2 \alpha) \text{ or}$$

$$A_c = \pi * d_c * d_w / \sin^2 \alpha \quad \text{[inch}^2] \qquad (15)$$

The area under one cord A_c includes the distance c to the next parallel cord and is for one full helical wrap:

$$A_{cr} = A_c * c/d_c = \pi * d_w * c / \sin^2 \alpha \qquad \text{[inch}^2] \qquad (16)$$

A_{cr} is the area under one cord plus the distance to the next cord in the woven cord fabric. The pressure of the tensioned cord on the area A_{cr} is with Equation (13):

$$p_i = P_i / A_{cr} = 2 * P_c * \sin^2 \alpha / (d_w * c) \quad \text{[psi]} \qquad (17)$$

For the two counter-helical cord layers in the hose the pressure becomes:

$$p_h = 2 * p_i = 4 * P_c \sin^2 \alpha / (d_w * c) \qquad \text{[psi]} \qquad (18)$$

It is necessary to express α, d_w, and c through the corresponding values α_0, d_{w0}, and c_0 for the relaxed hose, since only these values can be directly measured. From Figure 6 we get:

$$\sin^2 \alpha / \sin^2 \alpha_0 = \pi^2 * d_w^2 * l_{c0}^2 / (l_c^2 * \pi^2 * d_{w0}^2) = d_w^2 / (d_{w0}^2 * \lambda_c^2) \qquad (19)$$

With constant volume deformation, see equation (4), we can write:

$$(d_w / d_{w0})^2 = p_0 / p = \lambda_h^{-1} \qquad (20)$$

Combining equations (19) and (20) results in:

$$\sin^2 \alpha = \sin^2 \alpha_0 / (\lambda_c^2 * \lambda_h) \qquad (21)$$

The distance between two stretched cords c in equation (17) is substituted by c_0, the distance between two cords at zero hose elongation, see Figure 10:

It is: $\qquad\qquad\qquad\qquad \sin \alpha / \sin \alpha_0 = c * k_0 / (c_0 * k) \qquad (22)$

Or: $\qquad\qquad\qquad\qquad c = c_0 * \lambda_h * \sin \alpha / \sin \alpha_0 \qquad \text{[inch]} \quad (23)$

Finally the combination of equations (5), (18), (21), and (23) results in:

$$p_h = (4 * P_c * \sin^2 \alpha_0) / (\lambda_h * \lambda_c * d_{w0} * c_0) \qquad \text{[psi]} \qquad (24)$$

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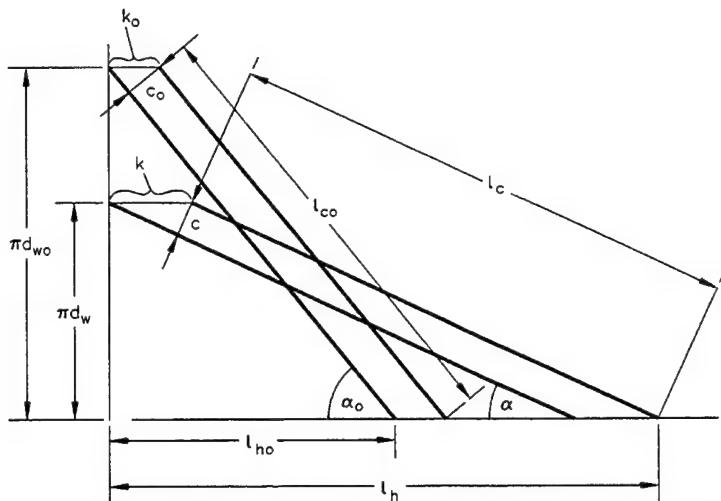
Figure 10:   Determination of distance between cords c in hose wall

For λ_c equation (8) can be introduced:

$$\lambda_c = [\ \lambda_h^2 * \cos^2 \alpha_0 + \sin^2 \alpha_0 / \lambda_h\ ]^{1/2} \qquad (8)$$

and equation (24) becomes:

$$p_h = (4 * P_c * \sin^2 \alpha_0) / [\ d_{wo} * c_0 (\lambda_h^4 * \cos^2 \alpha_0 + \lambda_h * \sin^2 \alpha_0)]^{1/2} \ [\text{psi}] \qquad (25)$$

1.2.4   Determination of the Axial Load in a Stretched Hose

The axial hose load P_h can now be calculated at a selected hose elongation ratio λ_h and cord elongation ratio λ_c, and the elastic modulus E_r of the rubber hose wall as:

$$P_h = N * \cos \alpha_0 * P_c * \lambda_h / \lambda_c + A_r * E_r * \varepsilon_h - p_h * A_b \quad [\text{lbs}] \quad (26)$$

Here N is the total number of tire cords in the hose wall, A_r is the hose wall cross sectional area filled by rubber, p_h the fill pressure generated by the tensioned hose [equation (25)] and A_b the area of the hose bulkhead (= the area calculated with the inner hose diameter). The cord tension $P_c = f(\lambda_c)$ is obtained from the tire cord's load-elongation curve.

1.2.4   Computer Program to calculate Stretch Hose Properties

The design calculations have been established as the "Snubber" computer program. The calculations determine in small increments of the hose stretch the response of the counter-helical cord geometry and hose wall cross sectional area. Input data are the cord wrap angle, the wrap diameter of the cords in the hose, the hose inner and outer diameter, the number of cords per inch, the rubber elastic modulus, and the nylon tire cord's load response to applied stretch. For each hose stretch the program calculates the cord stretch, the individual cord load from the given cord load elongation curve, the summation of the cord loads, and the rubber tension developed in the hose cross sectional area. Further the program calculates the sum of total cord load and rubber load, and the fill fluid pressure. The net hose tension is finally calculated after

subtraction of the cord load needed to support the bulkhead pressure. The hose elongation step size can be selected and is typically every 1 to 2.5 percent length increase to supply a sufficient number of data points to draw the hose load elongation curve and hose fill pressure elongation curve up to the breaking elongation of the nylon reinforcing cord. The safe working load is selected as the hose load at which the nylon tire cords are stressed to 1/3rd of their breaking strength, see Figure 11.
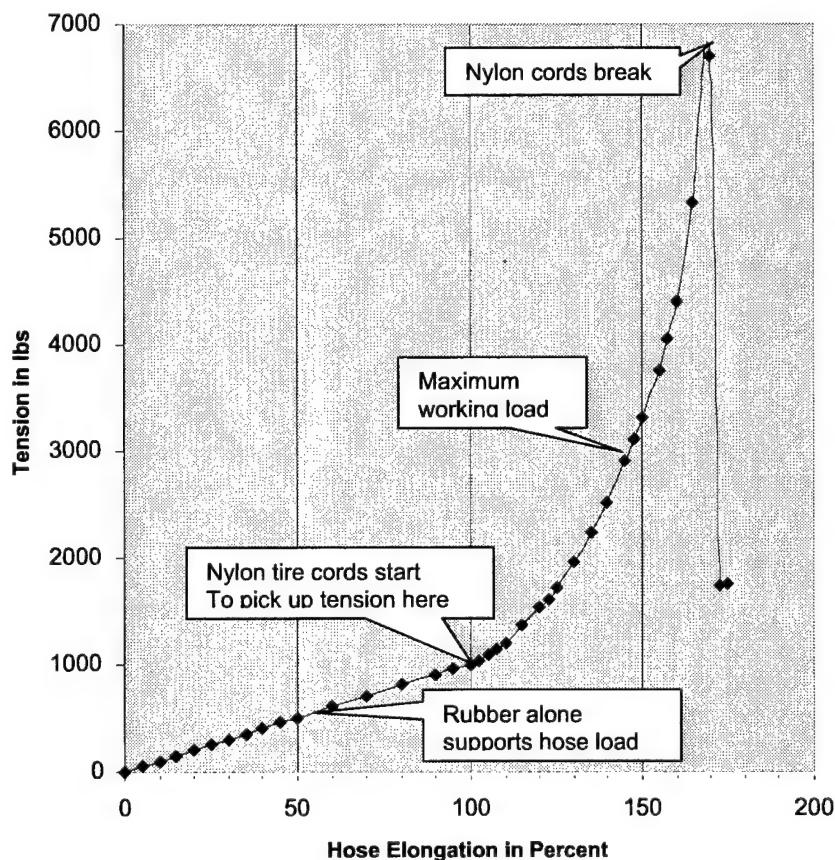
Figure 11: Calculated behavior of high stretch mooring hose with 68 degree wrap angle

2.0   FABRICATION

The hoses are hand laid up over a powered rotating steel pole or mandrel. The hose builder starts by placing hose couplings on the mandrel at each hose end. All hose wall components are rubber ribbons or rubber surrounding woven cord reinforcing ribbons cut to specified ribbon widths, see Figure 12. Construction begins with a spool of inner rubber material, which is wrapped over the mandrel and couplings to form the inner liner of specified thickness, see Figure 13. Over the inner liner one layer of rubber embedded nylon tire cord ribbon is wrapped at a specified wrap angle, see Figure 14.
The ribbon is cut to a width where butt wrapping the ribbon will result in the required wrap angle, see Figure 8 and equation (10). Next counter-helical stretch limiting layers of tire cord are applied near each hose termination. These layers are needed to reduce the hose stretch under load to near zero where the hose body is positioned over the coupling area to minimize abrasion between coupling and hose body, see Figure 15.

Figure 12: The building elements of hand laid up rubber hose are ribbons of rubber and rubber coated tire cord cut and spooled to specified width and length

Figure 13: Wrapping of the inner rubber liner of the hose

Figure 14:   Reinforcing layer of nylon tire cords is wrapped at specified wrap angle
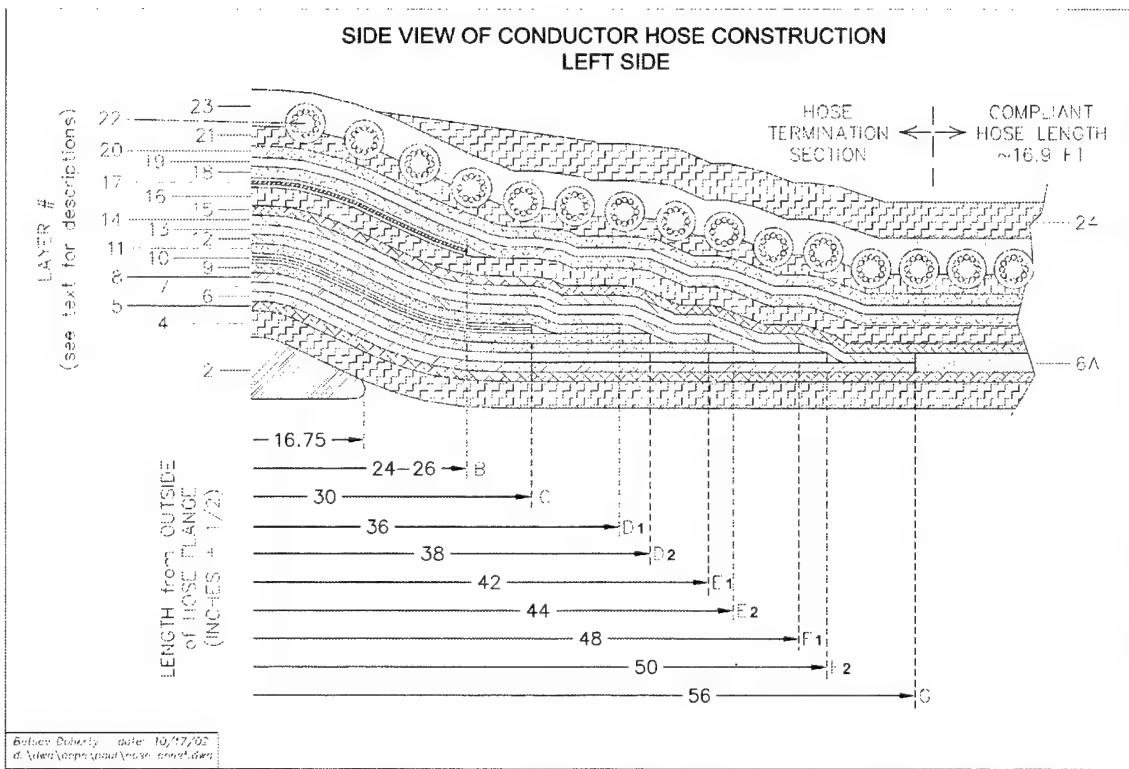
Figure 15: Side view of hose wall in termination area showing extra stretch reduction
          layers of tire cord. This hose has also electrical conductors incorporated.

A separation layer of rubber is applied over the first strength member layer, followed by a second layer of rubber embedded nylon tire cord. The second layer is wrapped in the opposite wrap direction as the first layer to form a near torque balanced overall response of the nylon strength member layers to applied loads. A rubber separation layer is applied next over the outer nylon strength member layer. The next step is the wrapping of two rubber embedded counter-helical layers of Kevlar tire cord for fish bite protection, or first the wrapping of a layer of electrical conductors, see Figure 16, and subsequently the wrapping of two counter-helical Kevlar layers, see Figure 17.

There is also a rubber separation layer between the first and second Kevlar layer. The conductors and Kevlar layers are wrapped at a steeper wrap angle so that they will not be stretched, just changed in their geometry, while the hose elongates under applied tension. Finally an outer rubber layer is forming the outer hose jacket. The rubber and tire cord layers are secured to the coupling with strong binding wire wraps, which press down on the steel tubing portion of the coupling. External steel rings, welded around the tubing, prevent the hose body from sliding off the coupling. After the hose is completed, pigtails of the electrical and possibly optical conductors are extracted from the hose body in the termination area. Subsequently the hose is covered with tight wraps of nylon fabric and vulcanized. The vulcanization process is exposing the hoses

Figure 16: Wrapping electrical conductor around the hose body

to 300^0 F steam for several hours in an autoclave, and causes shrinkage of the wraps of nylon fabric. This vulcanization process changes the rubber from a soft putty-like
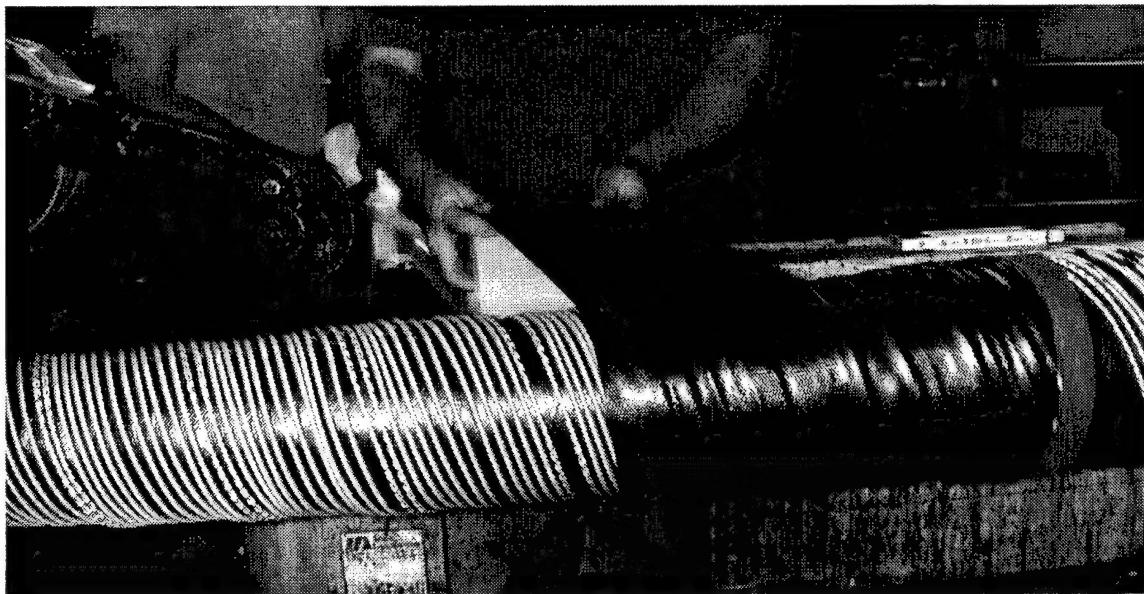
Figure 17 Covering the electrical conductors with a first rubber layer

material to a rugged tough surface with a tire-like feel. The outer nylon fabric wrap shrinks due to the steam and heat exposure and tightens the rubber and woven tire cord layers in their grip of the steel mandrel. After the curing process the nylon wrap material is unraveled, the mandrel is removed, and the hose is ready for shipment. The hose surface is showing the footprint of the fabric wrap. Electrical underwater connector pigtails are connected to the conductors to complete the hose assembly for deployment at sea, see Figure 18.
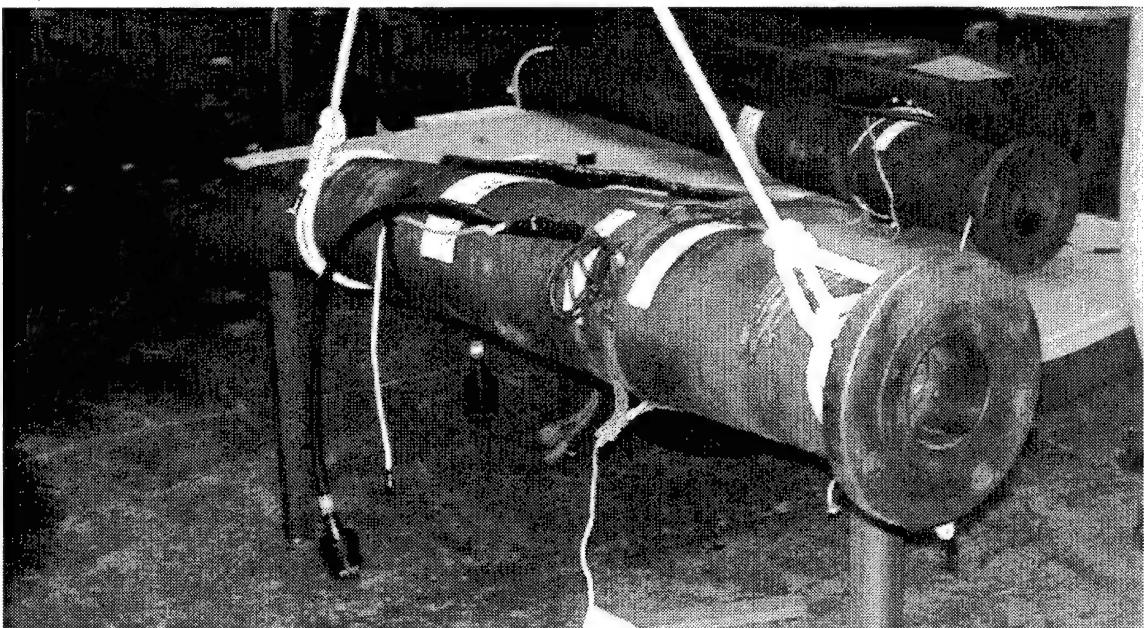
Figure 18:   Feed Hose is being furnished with Electrical Connector Pigtails at WHOI. Image shows connected electrical pigtails with plug-in connector before covering breakout area solidly with rubber and sealing tape.

3.0 HOSE TESTS

Three series of cyclic testing of three different stretch hose constructions were performed at TMT Laboratories in Huntington Beach, California. The first test was a tension plus flex test, the second and third test was a tension cycling test.
The first hose was an 8 ft long "Snubber" test hose, for which TMT built a special test machine combining a hydraulic ram tensioning piston with a "wagger". The wagger was built like a church bell drive to flex one hose end with an adjustable flex angle. The hose was simultaneously flex and tension tested. The 1994 test was stopped after a total of 1 million flex cycles and 600,000 tension cycles. The flex angle of +/- 30 degrees was much higher than what the hose should ever see in a mooring. The hose started to rupture the outer rubber jacket where the hose transitioned from its free length to the contact area with its molded in coupling due to the crowbar like forcing of the hose through the flex test at this area. The rest of the hose stayed intact.

The second and third set of cyclic tension fatigue tests was performed in 2000 test series (Walther et al, 2000). One hose was a medium high stretching hose with a 64^0 wrap angle of the main nylon strength members, the other hose was a high stretching hose with a 68^0 wrap angle of its nylon strength members. The lower stretching hose had a maximum stretch of 79% at its $115,000^{th}$ cycle to $1/3^{rd}$ of its theoretical breaking strength, the higher stretching hose had a maximum stretch of 130% at its $127,000^{th}$ tension cycle, again to $1/3^{rd}$ of its theoretical breaking strength. Figure 19 summarizes the test performance of both hoses, which passed the tests without mechanical damage.
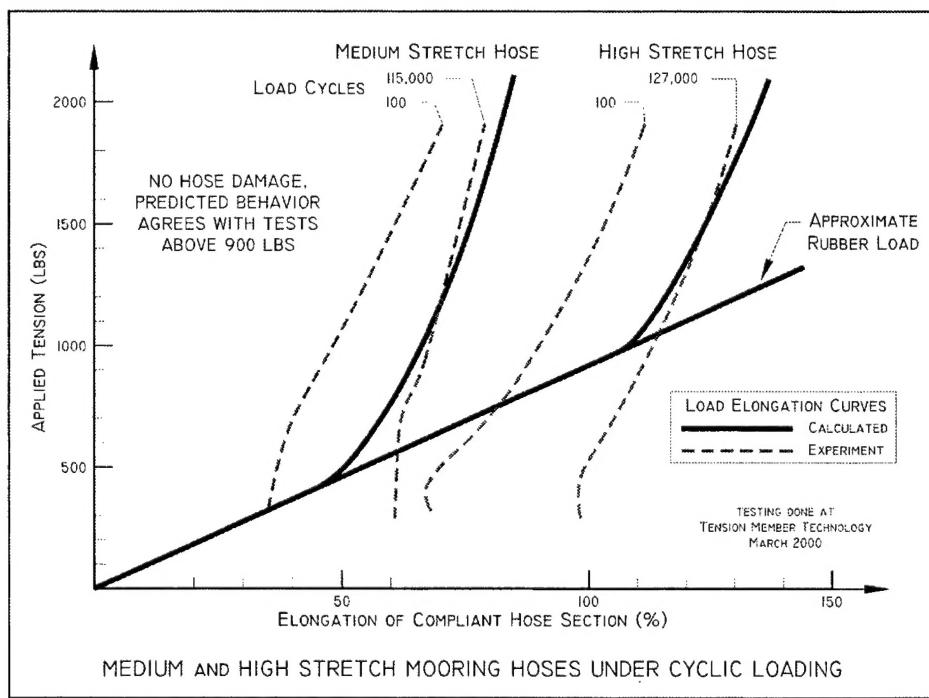

Figure 19 Load elongation behavior of medium and high stretch rubber hoses

The test programs showed that the hoses can survive a significant number of tension cycles without damage, testing them like the ocean does with about 500,000 tension

cycles plus a million flex cycles per month would require significantly higher test budgets.

4.0 HOSE PERFORMANCE AT SEA

Only a small number of hoses have been deployed in the ocean. In their first deployment in 1994 the hoses served as shock absorber as part of the SSAR drifting buoy mooring tethers. The drifting buoys ran out of battery power and can no longer be traced and monitored. One system was recovered and had traces of a shark bite attack. The shark bites did not penetrate beyond the Kevlar layer, and one shark tooth tip was caught in the hose. Otherwise the hose showed no signs of damage. A second short term deployment was in the Labrador Sea as part of a ROV docking station, see Figure 1. Currently one hose is working installed directly under the surface buoy of the MOOS mooring deployed by the Monterey Bay Aquarium Research Institute (MBARI) in 2,000 meter water depth. A highly stretching fish feed hose is installed below a surface feed buoy, connecting to a submerged net cage at the Open Ocean Aquaculture program of the University of New Hampshire. This hose serves also as electrical signal and power path to the net cage and allows researchers to video monitor fish behavior, water quality and other functions via telemetry link to its shore station, performing satisfactory for almost 18 months (status June 2004) at a fully exposed offshore site with 12 ft tides. A deployment in the second half of 2004 will use a 100 ft long high stretch mooring hose with electrical and optical conductors sandwiched into the hose wall. This hose will serve as a taut surface buoy mooring in 40 meter of water depth, to be deployed at the WHOI Buoy Farm site some 25 miles southwest of Woods Hole.

ACKNOWLEDGEMENT

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16. Abstract (Limit: 200 words)

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